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LIVE LOADING FOR LONG-SPAN HIGHWAY BRIDGES

By R. J. Ivy, A. M. ASCE; T. V. Lin, A. M. ASCE; Stewart Mitchell, M. ASCE; N. C. Raab, M. ASCE; V. J. Richey, A. M. ASCE; and C. F. Scheffey, J. M. ASCE

STRUCTURAL DIVISION

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PAPERS

LIVE LOADING FOR LONG-SPAN HIGHWAY BRIDGES

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Synopsis

The live loading used in designing highway bridges of short and medium spans is standardized by various codes, but the selection of a suitable live loading for long spans has been left to the discretion of the designing engineers. The writers have formulated herein a loading suitable for use as a design standard and a system of accompanying allowable unit stresses to provide for repetitions of stress and their effect upon highway bridges longer than 400 ft.

Introduction

The two standard codes now used for the design of bridges are that of the American Railway Engineering Association (11)[7] and that of the American Association of State Highway Officials (12) (AASHO). The former code applies to spans 400 ft and shorter, and the latter does not definitely state the limiting length for which the specifications govern; the AASHO does assert, however, that the live loading should be reduced for spans exceeding between 300 ft and 400 ft. The purpose of this paper is to furnish suggestions for such supplemental specifications concerning live loading and related subjects as are required for the design of long-span highway bridges.

Note.—The authors of this paper constitute a Joint Committee of the San Francisco, Calif. Section and Sacramento, Calif. Section, ASCE, as appointed November 15, 1950. Mr. Raab served as Joint Committee chairman. Wirtten comments are invited for publication; the last discussion should be received by **November 1, 1953.**

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[7] Numerals in parentheses, thus: (11), refer to corresponding items in the Bibliography (see Appendix).

Types of vehicles comprising the traffic on the various highways throughout the nation are quite varied, principally because of the nonuniformity of restrictions placed by the individual states on the size and weight of commercial carriers. The pattern of traffic including both automobiles and all the various types of trucks further complicates the problem of standardizing a live loading which could be used for long-span bridges.

The study for a design live loading for long-span highway bridges with related problems consisted of the following steps: (1) A review of the present status of live loading for highway bridges; (2) a review of loadometer station recordings; (3) a survey of long-span highway bridge traffic; (4) reduction of the data; (5) the formulation of design live loading; and (6) a study of related problems.

Various problems are interconnected with design live loading—such as reductions for multilane loadings, impact in long spans, fatigue of metals, economy, and safety. Most of these accompanying effects are being considered by other groups, and are therefore outside the scope of this paper.

Review of Present Status

Various types of loads have been used to represent the maximum live load using the highways. Formerly the live loading used for highway bridges consisted of a load per square foot of roadway, the intensity decreasing with the loaded length of structure. As roadway stripping became prevalent, the H and H–S type of lane loading became standard for the shorter spans (12). For the longer loaded lengths a uniform lane load with a concentration is now the most commonly-used method of evaluating the effects of live loading. A uniform load which is similar, but without concentration, is used by some engineers for the longer spans. On some projects, an empirical formula has been used, yielding a varying lane load, of which the intensity decreases in accordance with the loaded length.

The foregoing paragraph shows that there is no uniformity of practice regarding the design live loading for longer spans. Although some divergency might be unavoidable in order to meet the local conditions and special traffic requirements of a particular bridge, it is reasonable to assume that standardization of live loading for long spans is desirable.

Loaded Length

The "loaded length" of a span is the length of loading required to produce the maximum live load stresses in individual members or maximum reactions in supports. Loaded lengths for simple, continuous, or other types of structures are those lengths—or summations of lengths—producing the maximum stresses or reactions of the same sign in any member. All reference in this paper to loaded span length will mean the loaded length producing maximum stress.

Basis for Design Live Loading

The basis of design for any long-span live loading will depend in general on the three fundamental variables listed below: (1) The weight and type of

vehicles; (2) the vehicular pattern or arrangement of vehicles in a lane; and (3) the speed and spacing of vehicles.

Specific truck weights and truck types might not be representative of the vehicles traveling on all the various highways. The writers have endeavored, however, to select representative vehicle sizes, weights, and types recognized as legal in most states. An overweight truck would have a pronounced effect on the floor system of any structure or on any short-span structure; however, the longer spans are relatively insensitive to individual heavy concentrations.

The vehicular pattern, or arrangement of vehicles in a lane, varies momentarily because of the passing of the smaller and more manoeuverable vehicles. The pattern also changes by the particular hour, day, month, and year. The vehicular pattern affects the longer spans more than it does the shorter spans. One or more design loads of known value can be placed on the shorter span to produce the maximum effect. On the longer spans, the accumulative effect of many of the heavier trucks produces the maximum results. Although the pattern of vehicles varies, some standard might be chosen to serve as a common basis for design.

Most highways carry traffic composed of automobiles, buses, and trucks. This mixed traffic produces a very light lane loading. Generally, the maximum proportion of automobiles to heavier vehicles is in the ratio of 4:1, and will produce, under ordinary conditions, a lane load of between 150 lb and 250 lb per lin ft when operating at a very slow or zero speed with an allowance of about 8 ft between vehicles.

Even under mixed traffic conditions, it is conceivable that trucks alone could occupy traffic lanes for some distance, and some structures are built entirely for truck traffic. Also there are times when civilian traffic is stopped in order to allow military convoys to pass. These conditions should be considered for any live loading for long spans.

The live loading used in the AASHO specifications (12) and the loadings referred to in this paper do not represent the heaviest truck-and-trailer combinations using the various highways in the United States. This loading is the result obtained from normal legal vehicles using the various highways.

Traffic and Vehicular Surveys

When considering the bases for design live loadings, the writers studied actual data derived from traffic studies of the lower deck of the San Francisco-Oakland Bay Bridge, in California, which is devoted entirely to heavy vehicular travel; records of the heavier vehicular traffic taken from rural loadometer stations; and studies of the weights and arrangement of vehicles in military convoys traveling the highways during manoeuvers and under assignment.

To obtain a pattern of traffic on the lower deck of the San Francisco-Oakland Bay Bridge, a two-day count was taken during the peak hours. The lower deck of this bridge is composed of three 10.33-ft lanes carrying opposed traffic which uses the center lane for passing. Except for conditions peculiar to this particular bridge, these data are considered representative of segregated truck loadings which might exist on any long-span bridge. The information recorded was as follows: (1) The time of departure from toll gates; (2) classi-

fication of vehicles according to the number of axles; (3) the weight of the vehicle; and (4) the average speed of the vehicle during crossing.

Figure 1 lists truck classifications mentioned in this paper, with diagrams of the typical vehicles for each type. The wheel-base measurement for each typical vehicle also is shown in Fig. 1.

A typical pattern of truck loadings obtained from the survey is shown in Table 1. From these data it is interesting to note that the heaviest trucks did not generally follow one another. A loading of the heaviest trucks in regular pattern would be a rare natural occurrence or a planned, regulated trip.

The actual maximum lane load obtained for the observed speed in the two-day recording of these data was only 145 lb per lin ft of lane, which is much less than the 640 lb per lin ft of lane specified by the AASHO.

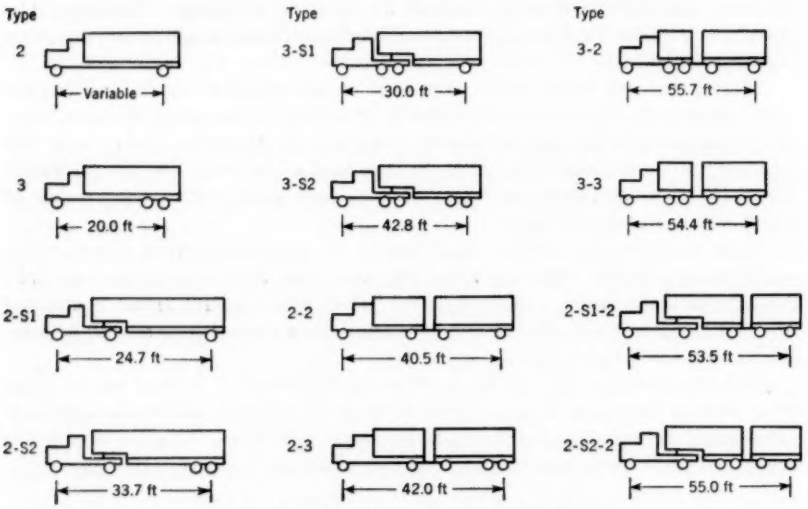


FIG. 1.—IDENTIFICATION OF TRUCK TYPES

The average weight of vehicles using the lower deck of the San Francisco-Oakland Bay Bridge is known to be less than the average weight of trucks using the highways. This is a result of the nature of the business the bridge handles and the restrictions placed on traffic using it. These factors may be summarized as follows: Short hauls, with 50% of the trucks either partly loaded or empty; prohibition of trucks carrying inflammable liquids; "peaking" of heavy bus and truck traffic at different hours; and busses which carry predominantely light loads after morning peak hours.

Records were obtained from various highway loadometer stations which showed samples of heavier vehicular loads than those found in the bridge study. Selected heavy trucks weighed at these stations averaged about 20% heavier than the vehicles using the lower deck of the San Francisco-Oakland Bay

Bridge. The actual loadometer-station pattern of the mixture of lighter trucks and heavier trucks was not obtained.

Weights and arrangement of military convoys were obtained from the manual (10) of the United States Department of the Army and from tables of organization and equipment for units such as an engineer combat battalion. This is one of the heaviest common units likely to use the highways. The average lane load with this type of unit spaced at 8 ft between vehicles is 620 lb per lin ft. The extremely heavy loads of the armored units, which would travel the highways only in an emergency, would follow normal military regulations of speeds and spacing in crossing bridges. Regulations specify 30 yd

TABLE 1.—TYPICAL TRUCK PATTERN (VEHICLE TYPES IDENTIFIED IN FIG. 1)

Typical axle types	Departure Time			Truck weight, in pounds	Average speed, in miles per hour
	Hour	Minute	Second		
2	8	34	25	3,400	....
2-S1	8	34	25	28,500	25.0
2	8	34	30	26,900	30.5
2-S1	8	34	40	20,000	31.0
2	8	34	55	26,500	....
3-S2	8	35	00	56,000	26.1

between vehicles; according to this restriction, the average lane load for a medium tank battalion is found to be 450 lb per lin ft.

REDUCTION OF TRAFFIC DATA

Before reducing the traffic data to a design live loading, speed and spacing of vehicles must be considered. In the case of the survey at the San Francisco-Oakland Bay Bridge, it was found that the average speed for all vehicles making the crossing was 34 miles per hr, although the posted speed limit for this deck is 35 miles per hr. The minimum average speed recorded was 18 miles per hr. and some stoppages occurred that resulted in zero speed.

To relate truck spacing to truck speed, the following equation was used:

$$D = K_1 v^2 + K_2 v + L + L' \quad \ldots\ldots (1)$$

in which D is the safe following distance between centers of vehicles, in feet; K_1 is the vehicle braking constant, equal to 0.05; K_2 is the driver reaction constant, equal to 1.50; L is the length of the vehicle, in feet; L' is the minimum clear distance between vehicles, taken as 8 ft; and v is the velocity, in miles per hour.

The lane capacity, C, in vehicles per hour, may be obtained from the expression:

$$C = 5{,}280 \frac{v}{D} \quad \ldots\ldots (2)$$

If the weight of a vehicle, in pounds, is denoted by the symbol W, the average

lane load, in pounds per lineal foot, is expressed as

$$w = \frac{W}{D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

An average clear distance of 8 ft between two vehicles was measured in the field. This is the minimum space required for one vehicle to turn out and pass

TABLE 2.—AVERAGE WEIGHT AND LENGTH OF TRUCK

Truck type (see Fig. 1)	Average weight, in pounds	Overall length, in feet	Number of trucks	Total weight, in kips	Total length, in feet
2	4,604	15.0	2,429	11,184	36,435
2	11,022	20.0	1,322	14,571	26,440
2	23,553	25.0	608	14,320	15,200
2-S1	24,568	29.7	367	9,017	10,900
2-S2	32,909	38.7	248	8,161	9,598
3-S2	44,088	47.8	209	9,214	9,990
3	17,547	25.0	177	3,106	4,425
2-S1-2	45,263	58.5	139	6,292	8,132
Others	48,264	57.8	130	6,274	7,514
Total			5,629	82,139	128,634
Average	14,592	22.9			

another when given the opportunity. Under no conditions were vehicles found stopped bumper to bumper.

To determine average length and weight of vehicles, the total truck traffic recorded during the period of the survey is recorded in Table 2. A total of 5,629 trucks passed through the tollgates during these two 7-hr periods, yielding

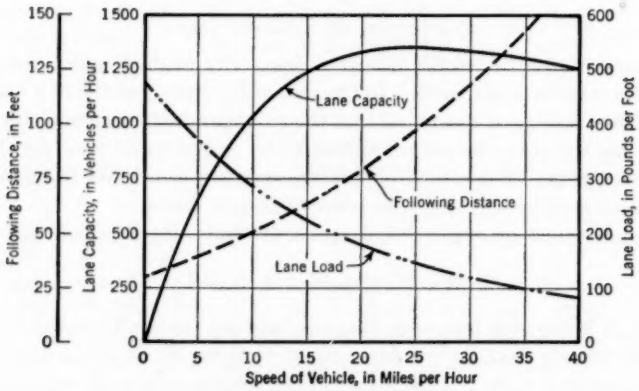


FIG. 2.—LANE LOADING CHARACTERISTICS

data from which was derived an average truck weight of 14.6 kips and an average length of 23 ft. Eq. 3 yields $\frac{W}{D}$ = 472 lb per lin ft, in which D is the sum of the average overall length plus L'.

The average lane load for zero speed according to the information from one of the loadometer stations is 589 lb per lin ft. This loading is somewhat

greater than the average loading of all trucks using the highways, because only the larger and heavier loaded trucks are weighed at the loadometer stations; the loading recorded at these stations, therefore, would not be typical of the truck pattern to be discussed.

The lane capacity, following distance, and lane load for various speeds are tabulated in Table 3 and illustrated graphically in Fig. 2. The maximum lane capacities are obtained between speeds of 20 miles per hr to 30 miles per hr; the maximum lane load, however, is obtained at zero speed. The lane capacity for any structure depends on the physical characteristics of the particular lane—such as width, grades, alinement, shoulders, side obstructions, and other conditions. Lane capacities are also influenced by speed, safe following distances at various speeds, length, weight, and manoeuverability of the vehicles.

The average truck listed in Table 2 is a composite vehicle representing all of the trucks recorded during the survey. The lane loads found on the basis of the composite truck (shown in Table 3) are of interest because they apply only to extremely long spans. These lane loads would be the lower limits for any live loading derived from the survey data. For shorter spans, the

TABLE 3.—LANE CAPACITIES AND LOADS

Speed, in miles per hour	Following distance, in feet	Lane capacity, in vehicles per hour	Lane loads, in pounds per foot
0	30.9	0	472
5	39.7	660	365
10	50.9	1,040	285
15	64.7	1,220	225
20	80.9	1,305	180
25	99.7	1,320	145
30	120.7	1,310	120
35	144.7	1,275	100
40	170.9	1,240	85

lane load would depend on the actual traffic patterns and would vary inversely with the loaded length. Actual patterns of the survey data were plotted, samples of which are shown in Fig. 3. In plotting these truck trains, the actual pattern at the toll gates was maintained. However, the spacing between the trucks has been shortened to a minimum of 8 ft. Any long-span bridge will have at least two lanes, and simultaneous loading of two lanes with a pattern giving the maximum loading was considered improbable. Therefore, it was decided to use the maximum loading in one lane, averaged together with the loading for the same time period of the following day of the survey in the opposite lane. With these loading patterns established, uniform lane loads producing the same maximum moment and shear stresses, and producing maximum average lane loads were determined for various loaded lengths. These equivalent loadings are shown in Fig. 4.

DESIGN LIVE LOADING

At first consideration of the establishment of a suitable live loading, it might appear that the pattern of mixed live loads found on the various high-

ways and freeways in the United States should be the basis for any study of live loading.

However, the studies made in this paper indicate that a loading suitable for design purposes could not be obtained from a pattern composed of mixed traffic occurring on the various highways, because of the high ratio of auto-

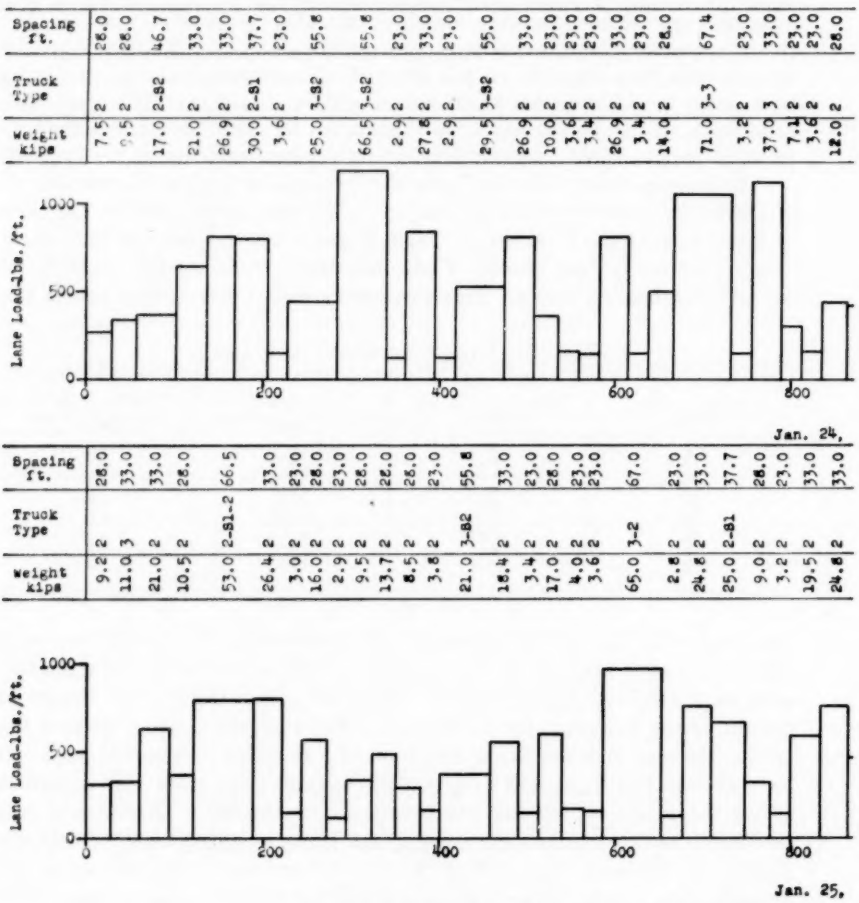


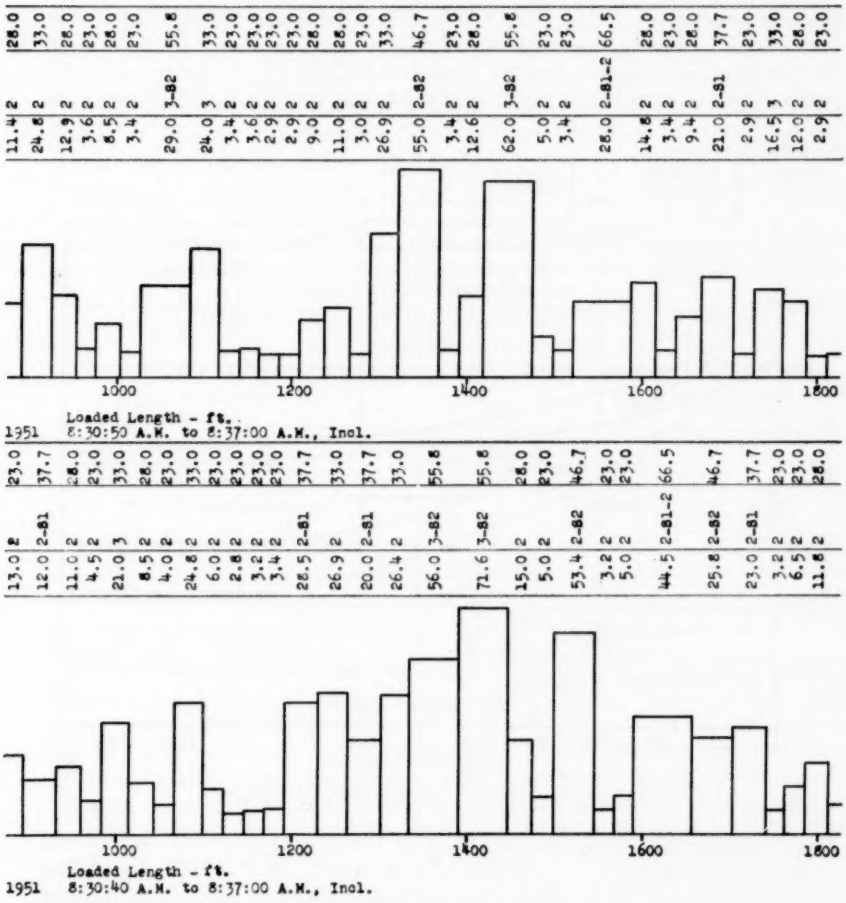
FIG. 3.—TYPICAL TRAFFIC PATTERN FOR THE LOWER DECK OF THE

mobiles to trucks. This loading would be too light and would not account for the probability of the increased number, if not weight, of trucks in the future.

The nearest approach to a maximum live loading, therefore, would seem to be the loading pattern of a military convoy occupying the entire length of a structure, or truck and bus traffic such as that which uses the lower deck of the San Francisco-Oakland Bay Bridge. This latter loading, which excludes auto-

mobiles, has been found fairly representative of convoys that normally use the highways.

The variables involved make it evident that a single pattern for any one lane and for any one length should not be taken as a standard and applied to all lanes of a bridge. It is assumed that any modern bridge would have not



San Francisco-Oakland Bay Bridge—Westbound Traffic

less than two lanes, particularly a long-span structure on which the ratio of the width to the span would have to be maintained; consequently, the average of two typical lane patterns would be applied for any loaded length desired. The probability of having more than two lanes occupied by this average lane loading is provided for by the reduction factor in the AASHO design specifications (12).

A comparison of the data on heavy vehicles shows that the average truck on the highway is slightly heavier than the vehicles using the lower deck of the San Francisco-Oakland Bay Bridge. However, the total vehicular load on the highway is much less because the ratio of automobiles to trucks is between 4:1 and 5:1. It was decided to use the bridge pattern of loading because: (1) It more nearly fits the military convoy loading—which, it is believed, would be the only heavy loading that would occupy the entire length of a structure under restrictions. (2) The reserve factors of safety, resulting mainly from the large ratio of dead load to live load for long-span bridges, could absorb any overloading from a regulated grouping of the heaviest trucks without jeopardizing

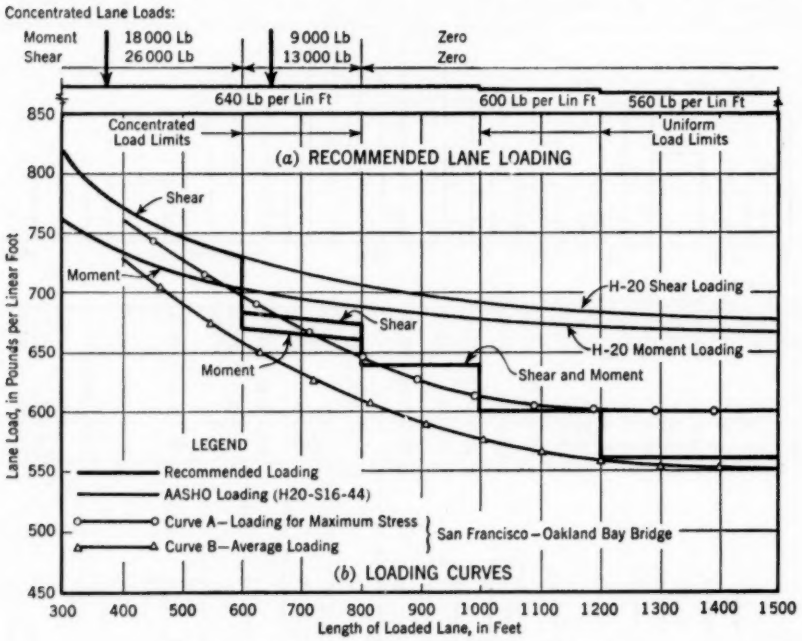


FIG. 4.—LIVE LOADING CURVES FOR LONG-SPAN BRIDGES

the structure; this, however, would not be the typical everyday loading and would probably never occur in the life of a structure. (3) The vehicular loading of a highway would in all cases carry mixed traffic which, in turn, would produce a lighter load than that assumed for the convoy load.

Several forms of loading were considered which would accurately, yet simply, represent the typical heavy vehicular pattern. It would appear, because of general usage of the AASHO live load, that some form of loading similar to this should be used for the longer spans. The recommended loading of Table 4, illustrated in Fig. 4, satisfies the vehicular pattern data and is in a form familiar to most designers.

Consideration was given to the types and limiting lengths of structures which would use this type of loading.

Plate-girder bridges of one span or of more than one span, either simply supported or continuous, are usually limited by specifications to lengths not greater than 300 ft between supports. For continuous bridges, the concentrated loads should be placed so as to yield maximum reactions or stresses.

Simple-span truss bridges for highways have maximum lengths of between 500 ft and 600 ft. Here again, concentrated loads should be used to give the effect of local concentrations represented in the traffic patterns of Fig. 3.

Structures with clear spans of between 500 ft and 1,000 ft are generally cantilever bridges or continuous truss bridges. Members designed by the shorter loaded lengths will have the benefit of the concentrations. Main truss members, because of the longer loaded lengths, will be proportioned by the uniform load.

If spans are greater than 800 ft, the suspension-type bridge is nearly always considered, provided conditions at the site are favorable. Concentrated loads

TABLE 4.—Recommended Maximum Live Loading for Long-Span Bridges

Loaded Length, in feet		Uniform live load, in pounds per linear foot of lane	Concentrated Live Load, in pounds	
Minimum	Maximum		For Moment	For Shear
0	600	640	18,000	26,000
600	800	640	9,000	13,000
800	1,000	640	0	0
1,000	1,200	600	0	0
1,200	∞	560	0	0

are difficult to apply in the analysis of a structure of this type, and the effect of concentrated loads on spans of 800 ft or greater is negligible.

This load provides a gradual reduction in intensity from the short bridges to the long-span bridges; however, sudden changes in live-load stresses will occur at the loaded lengths where the loadings change. These changes in both the web and chord stresses are less than 8% for the live load, and less than 2% when both live load and dead load are considered. The proportions of a member are ordinarily not changed for a variation of stress of this magnitude.

Figure 4 shows graphically the variation of lane loads for different loaded lengths. The AASHO H20-S16-44 loading is included for comparison. Curve A represents the uniform lane load that will produce maximum flexural stresses and shear stresses; Curve B represents the maximum average lane load. Both curves are obtained from traffic patterns with two lanes loaded such as those shown in Fig. 3. Curves A and B envelop the curve representing the recommended live loading for long-span bridges.

Related Subjects

The relationship between the live-load stresses and dead-load stresses in highway bridges does not remain constant with an increase of span; the live

loading decreases somewhat, whereas the dead load increases more rapidly as the span increases.

Naturally, these ratios of live load to dead load will vary (even in spans of the same length) according to the width of the roadway, the type of loading, and other variables peculiar to a particular structure. Ratios of live load to dead load for various component parts of typical spans between 300 ft and 1,000 ft are listed in Table 5.

Attempts have been made to provide for the damaging effects of repeated stresses and for future increase in live loadings, by increasing the factor of safety for those parts which come into more direct contact with the live loading. The proportioning of these effects in the design of a structure has come to be

TABLE 5.—LOAD RATIOS, STRESSES, AND SAFETY FACTORS FOR VARIOUS BRIDGE COMPONENTS

Member	RATIO OF LIVE LOAD TO DEAD LOAD		UNIT STRESS, IN POUNDS PER SQUARE INCH		SAFETY FACTOR	
	300-ft span	1,000-ft span	300-ft span	1,000-ft span	300-ft span	1,000-ft span
Slab	28.0:1	28.0:1	18,200	18,200	1.8	1.8
Stringers	4.0:1	3.0:1	19,200	19,500	1.7	1.7
Floorbeams	2.0:1	1.0:1	20,000	21,000	1.7	1.6
Verticals	1.1:1	0.7:1	20,800	21,500	1.6	1.5
Hangers	0.8:1	0.6:1	21,400	21,800	1.5	1.5
Web Members	0.6:1	0.2:1	21,800	23,000	1.5	1.4
Chords	0.3:1	0.2:1	22,600	23,000	1.5	1.4

known as "balanced design," and for large structures it is generally accomplished by either of the following two methods:

1. Dual unit stresses are used, whereby the specified unit stress is applied to the live load and a higher unit stress, usually one third greater, is applied to the dead load; or
2. The live loading is increased from that normally specified, and a higher unit stress is applied to both dead loads and live loads.

These two methods can be used with equal ease and success. If the first method is used all dead-load stresses are reduced by one fourth and the unit stress applying to the live load is used. This method may be preferred because it is adaptable to any specification and no change is necessary in the unit stresses established, and because it does not imply that the established live loading should be increased.

Using the first method and applying unit stresses of 18,000 lb per sq in. for live load and 24,000 lb per sq in. for dead load, for members of carbon steel with an elastic limit of 33,000 lb per sq in., the combined unit stress and the factor of safety are listed in Table 5. The stresses listed are based on the corresponding ratios of dead load to live load. The lesser factors of safety are applied to the members carrying predominately dead load.

The dead load of a bridge can, in general, be divided into two parts: (1) The floor system, including the slab, stringers, and floorbeams; and (2) the

trusses, including the longitudinal and transverse bracing. In very short spans, the weight of the floor system is generally greater than that of the trusses.

It can be visualized that as the span length increases, the quantity of material used in the trusses exceeds that used in the floor system. The increase of truss material does not vary directly with, but as some power of, the span length. Also, as the span length increases, the distance on centers of trusses is increased to keep a satisfactory ratio of width to span. In turn, this change increases the length and weight of the bracing. The floor system, except for the floorbeams, increases directly with the bridge width. The floor system, even for the longer spans, will retain a somewhat constant factor of safety while the factor of safety for the trusses varies inversely with the span length.

The writers believe that an impact factor similar to that recommended by the AASHO should be retained even for the longer spans until better data are available. The intensity of impact varies inversely as the loaded length, and is in accord with the statements of the preceding paragraph.

Conclusion

The highway-bridge live loading presented in this paper for spans exceeding from 300 ft to 400 ft has been patterned after the present H20-S16-44 lane loading of the standard specifications of the AASHO (12). This type of loading is known universally and is commonly used in the United States. The live loading for long-span bridges, as described in this paper, accurately represents the survey data and the actual vehicular patterns indicated in this data.

Various methods to achieve balanced design for larger structures have been used. This has generally been accomplished by allowing greater dead-load unit stresses, so that the individual members of a structure can function more efficiently in their stress-carrying capacity.

The writers present this paper with the hope that it will stimulate widespread interest and further activity in the standardization of specifications for long-span highway bridges.

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